A Performance Assessment Review Tool for the Proposed Radioactive Waste Repository at Yucca Mountain, Nevada, USA

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1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC), with the assistance of the Center for Nuclear Waste Regulatory Analyses, has developed a Total-system Performance Assessment (TPA) Code [1] to assist in evaluating the performance of the Yucca Mountain (YM) High-Level Waste Repository in Nevada, proposed by the U.S. Department of Energy (DOE). The proposed YM repository would be built in a thick sequence of partially saturated volcanic tuff above the water table. Among the unique challenges of this environment are (1) the transport of radionuclides would take place partially through highly heterogeneous unsaturated rock; (2) the waste packages (WPs) would be generally exposed to oxidizing conditions, and (3) water either infiltrating from the surface or recirculating because of decay heat may drip onto the WPs.

Tools such as the TPA code and embedded techniques for evaluating YM performance are aimed at (1) determining the parameters and key parts of the repository system that have the most influence on repository performance; (2) performing alternative conceptual models studies, especially with bounding models; (3) estimating the relative importance of the physical phenomena that lead to human exposure to radionuclides; and (4) improving NRC staff capabilities in performance assessment and associated license application reviews. This paper presents an overview of the NRC conceptual framework, approach to conducting system-level sensitivity analyses for determining influential parameters, and alternative conceptual model studies to investigate the effect of model uncertainties.

2. COMPUTATIONAL MODELS

The basic conceptual models in the TPA approach that describe the interactions and couplings of the physical and chemical processes can be grouped into the following categories (see Figure 1): (1) precipitation, infiltration, and deep percolation, (2) near-field environment, (3) failure of engineered barrier system (EBS), (4) disruptive events, (5) radionuclide release from the EBS, (6) aqueous-phase radionuclide transport in unsaturated and saturated zones, (7) airborne transport from extrusive volcanism and (8) exposure to the reference biosphere (dose from groundwater and ground surface releases). This paper briefly describes the NRC conceptual models for the YM repository based on the DOE Viability Assessment (VA) design [2]. Since TPA uses Monte Carlo techniques requiring hundreds to thousands of computations (i.e., realizations), all models are highly simplified and abstracted from more complex models.

2.1 Precipitation, infiltration, and deep percolation

The unsaturated zone (UZ) model assumes percolation of meteoric water at the land surface vertically downward through the repository, and ultimately to the water table. The deep percolation flux is calculated from knowledge of present-day percolation at the site, taking into consideration climate changes, elevation, and soil-depth on the mountain. The effects of site-specific soil cover thickness and elevation are used to reflect the spatial variation over each of the subareas of the repository. The temporal and spatial variation of infiltration was developed from paleo-climatic information using detailed process-level analysis [3].

2.2 Near-field environment

The near-field environment model calculates the physical and chemical processes in the near field, which are affected by repository heat and how heat alters the chemistry and hydrology of the rock. The model calculates rock and WP surface temperature, relative humidity, water chemistry, and water reflux. The temperature model considers conduction, thermal radiation, convection and latent heat transfer. Estimates of pH and chloride concentration are calculated externally using a geochemical code [4].

2.3 Failure of EBS

The WP is the major component of the EBS. This model considers WP failure by corrosion of WP, rock-fall, undetected manufacturing defects and disruptive events such as seismicity and igneous intrusion. For the case evaluated (viability assessment), the WP would be constructed of an inner shell of corrosion-resistant nickel alloy and an outer shell of carbon steel. Corrosion of the outer barrier commences when the relative humidity (RH) at the WP surface exceeds a sampled critical value. Corrosion of the inner shell by either pitting or general corrosion is assumed to be possible under conditions of high RH or dripping, once the outer barrier has been penetrated. No radionuclides can escape the WP until it has been penetrated by at least one pit. We assume that there would be a small number, about 0.1 %, of WPs failed at the time of repository closure, as a result of fabrication defects and damage.

2.4 Disruptive events

There are three classes of disruptive events that could lead to radionuclide releases: seismic activity, fault displacement and volcanism. Seismicity can cause the WPs to fail mainly by inducing large rocks to fall into the excavated tunnels on the WPs [5]. Fault displacement could cause failure by shearing of WP. Igneous intrusions can fail WPs in the repository, leading to early release of dissolved contaminants. Extrusive volcanism can fail WPs, and also carry their contents to the surface and into the air.

2.5 Radionuclide release from EBS

The waste form, either uranium dioxide, uranium metal, or glass will degrade in the presence of air and water. Cladding on commercial spent fuel waste is assumed to fail totally or partially at randomly chosen times. Failed cladding is assumed to partially protect the waste form. Commercial spent nuclear fuel (CSNF) constitutes the bulk of the waste. Fuel is assumed to dissolve only in the presence of water, which comes into contact either by immersion (bathtub model), or dripping (flowthrough model). Water must fill the failed WP to an assumed overflow height before radionuclides leave the WP. In the flowthrough model, the fraction of fuel wetted is the same as the fraction immersed in water in the bathtub model, but radionuclides can leave upon WP failure without water filling the WP.

Most of the radionuclides are assumed to be released from the fuel at the rate that the fuel degrades or dissolves in water. Volatile elements (e.g., iodine) are assumed to be partially available as soon as the WP fails. There are several alternative models for CSNF dissolution in

TPA; two are based on assumptions about water chemistry in contact with the waste. Another assumes equilibrium with the uranium mineral schoepite. The dissolution rate also depends on the assumed average surface area of the exposed fuel, fraction of fuel wetted, and flow through the waste package. There is assumed to be one representative WP for each of the 7 subareas of the repository. However, each subarea may be run several times to represent either corrosion failures, premature failures, or disruptive event (e.g., volcanism, seismicity) failures.

Once released from the WP, the radionuclides first pass through the invert (the material under the WPs), which allows for radionuclide decay, diffusion and retardation. If the infiltration rate exceeds the saturated hydraulic conductivity of the invert, then rapid fracture flow is assumed and that leads to the bypass of this model, and the source term goes directly to the unsaturated flow zone (UZ) model.

2.6 Unsaturated and saturated zone flow and transport

Transport through the UZ below the WPs is assumed to be in parallel, one-dimensional flow paths with non-steady, vertical flow. The model allows for advection, longitudinal dispersion, matrix diffusion for fractured-porous media, and radioactive decay. Transport through the saturated zone is assumed to be in four parallel, steady flowing tubes with advection, longitudinal dispersion, matrix diffusion and radioactive decay. Radionuclides travel through several zones characterized as fracture-matrix and porous flow before reaching the assumed points of groundwater use. The one-dimensional stream tubes were derived from an external two-dimensional modeling study of sub-regional flow [6].

2.7 Airborne transport from extrusive volcanism

Doses to the exposed groups associated with extrusive volcanism are calculated by modeling releases of radionuclides in the airborne plume. The volcanism module assumes that magma intercepts WPs, moves upward to the surface, and then ejects the ash and SF mixture to the atmosphere. Three primary factors determine the ash plume transport; (1) power and duration, (2) wind speed and direction (although we considered wind only blowing in the direction of the critical group) and (3) SF particle size. The ash transport model of Suzuki [8] was modified to take into account the ash blanket thickness, leaching and erosion rates and radionuclide decay rates. Doses are strongly influenced by the timing of the event, with early events resulting in larger doses.

2.8 Exposure to the reference biosphere

Two possible exposed groups are evaluated: (1) a farming community of 100 families located 20 km downgradient from the site, and (2) a residential community less than 20 km from the site. The average member of the designated receptor group is assumed to be exposed to radionuclides transported through the groundwater pathway, air pathway, or both. Dose results from ingestion, inhalation, and direct exposure. Both groups are assumed to obtain dose through inhalation and direct exposure to ash-CSNF particles. For the farming community, we assume that all radionuclides released from the repository to the groundwater (except for the fraction decayed) will eventually be taken up in user wells. Doses are based on the amount of radionuclides dissolved in groundwater reaching the wells, mixed into the total quantity of water used by the community. The exposed group is assumed to get the average concentration for this withdrawal. Groundwater dose pathways include typical uses such as drinking water, irrigation, and stock watering. Only drinking water is considered for the residential community. Dose conversion factors (DCFs) are mean values generated through separate pathway calculations using the GENII-S code [7]. There are separate sets of DCFs for present-day and pluvial climates.

3.0 UNCERTAINTY AND SENSITIVITY ANALYSES

TPA was usually run in the probabilistic mode, using Latin Hypercube Sampling (LHS) [9]. A total of 246 sampled parameters were sampled and up to 1000 repetitions were made per problem. The LHS runs were used to evaluate the mean doses, and also perform sensitivity analyses of the base case and several alternative conceptual models. The base case model reflects the current repository design and likely parameter ranges for processes affecting repository performance. Key features of the base case are: (1) no cladding protection of SF, (2) dissolution of SF based on current saturated groundwater chemistry, (3) the "bathtub" model for fuel/water contact, (4) no matrix diffusion in the UZ and (5) no volcanism or faulting.

The ultimate output of the TPA code is usually framed in terms of the peak dose to an average member of the critical group. From the set of Monte Carlo realizations for each conceptual model, we evaluated the peak dose in two distinct ways. The first, more conventional way is to take the peak dose calculated for each realization and tabulate it. The average of the ensemble of peak doses is then reported. This procedure is known as the "mean of the peaks." Alternatively, the average dose for the ensemble of all runs was calculated at each time interval. The peak of this average dose was then reported. This procedure is referred to as the "peak of the mean" dose, and is always lower than the mean of the peaks. Currently, the staff has decided that the peak of the mean is a fairer representation of risk because it correctly weighs the range of potential doses to an individual during a single lifetime, and is more in line with the NRC's directive to make regulations risk-informed and performance-based. The peak of the mean dose is specified in NRC's draft rule for the Yucca Mountain repository [10].

3.1 Sensitivity

Several techniques that were used in the sensitivity analysis included regression-based methods, differential analysis, design of experiment-based method, Fourier Amplitude Sensitivity Test method, parameter-tree approach, and student's t-statistics. Parameter sensitivity analyses used peak dose from each realization as the performance measure. However, we used the peak of the mean dose when comparing alternative conceptual models. Staff performed sensitivity analysis on peak dose because the technique had not been developed yet for the sensitivity analysis of the mean dose.

Sensitivity was determined for 10,000 and 50,000 years. For both times, only a few of the 246 parameters were found to be influential for the most likely scenario: (1) areal fraction of the repository wetted by water, (2) a factor that expresses the focussing of flow reaching a WP, (3) the well pumping rate for the critical group, and (4) alluvium matrix sorption coefficients for Tc-99 and I-129. Parameters that were influential for 10,000 years, but not for 50,000 years, are: (1) initially defective fraction of WPs, (2) the fraction of water infiltrating to the repository from the unsaturated zone above the repository that will enter the WP and (3) the areal average mean annual infiltration. The only parameter that was significant for 50,000 years, but not 10,000 years, is the alluvium retardation coefficient for U-234.

The influential parameters were used to identify which of NRC's 14 integrated sub-issues (grouped events and processes or physical phenomena) are important to repository performance. The conclusion on relative importance of the parameters was reached by examining the number of times each of the parameters appeared in the top group identified by the various sensitivity measures. This implies that if a parameter was identified as influential by the majority of the sensitivity analysis methods, the integrated sub-issue associated with that parameter is significant. The majority rule was considered acceptable because no individual sensitivity analysis method was found uniquely superior to other methods. Further investigations are currently underway to determine more suitable methods for handling large parameter sets with multiple correlated parameters sampled over a broad range. A suitable method is yet to be developed for combining sensitivity analysis results from the high consequence low probability scenarios with results from the most likely scenarios.

3.2 Alternative Conceptual Models

Alternative conceptual models included disruptive events such as faulting and volcanism, alternative understanding of the physical processes such as bathtub versus flow-through model of the WP, and different models of fuel dissolution. Figure 2 shows a comparison of some of the alternative conceptual models with the base case model for 10,000 years. This figure shows the large sensitivity of dose to assumptions made in the EBS model.

4.0 CONCLUSIONS

The analyses and results demonstrate only a snapshot of NRC's performance assessment capability that is being continually updated. NRC's models and approach are based on a specific design, simplifying assumptions, and sparse data in certain areas. The performance assessment methodology presented in this paper has aided NRC staff in conducting risk-informed performance-based evaluations by focusing their attention on a limited but significant set of integrated sub-issues and providing specific pre-licensing guidance to DOE on the models and parameters that significantly influence DOE's safety case.

5.0 ACKNOWLEDGMENTS

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6.0 REFERENCES

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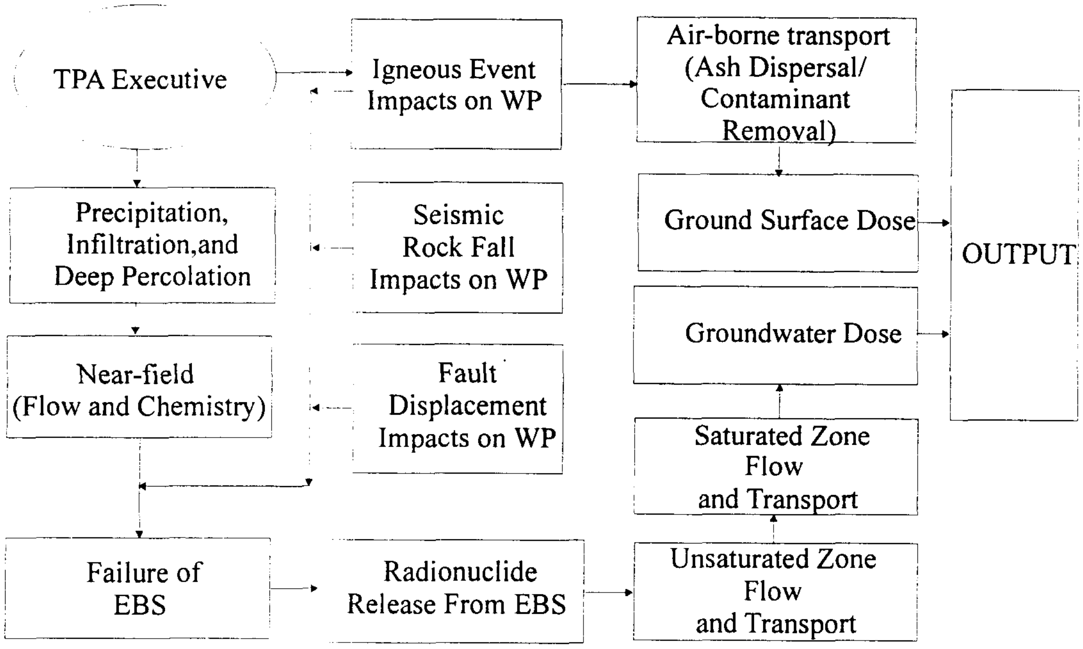

Figure 1. Flow diagram for TPA Version 3.2 code

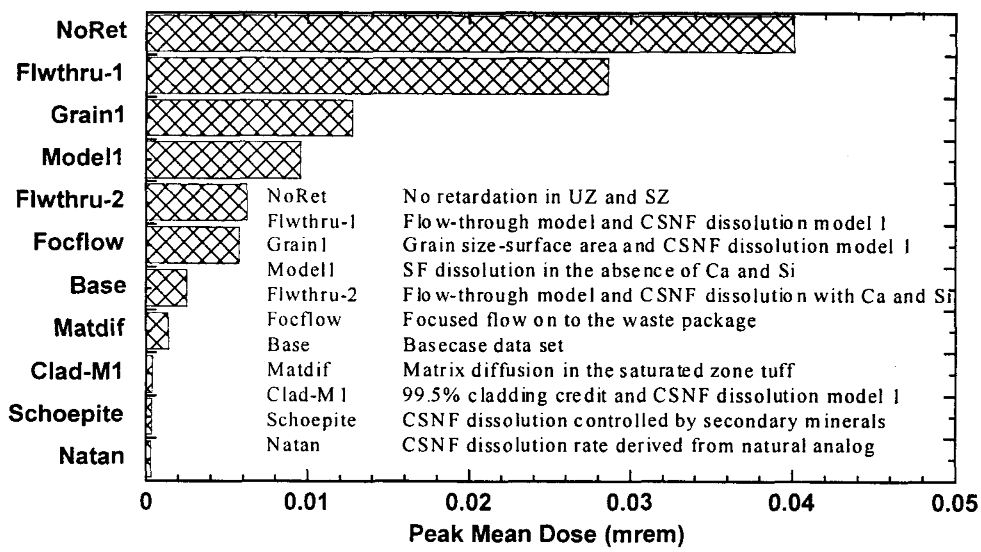

Figure 2. Bar chart showing the effects of alternative conceptual models at 10,000 yr